



Search for heavy resonances in the W/Z-tagged dijet mass spectrum in pp collisions at 7 TeV

CMS Collaboration *

CERN, Switzerland

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ABSTRACT

A search has been made for massive resonances decaying into a quark and a vector boson, qW or qZ , or a pair of vector bosons, WW , WZ , or ZZ , where each vector boson decays to hadronic final states. This search is based on a data sample corresponding to an integrated luminosity of 5.0 fb^{-1} of proton–proton collisions collected in the CMS experiment at the LHC in 2011 at a center-of-mass energy of 7 TeV. For sufficiently heavy resonances the decay products of each vector boson are merged into a single jet, and the event effectively has a dijet topology. The background from QCD dijet events is reduced using recently developed techniques that resolve jet substructure. A 95% CL lower limit is set on the mass of excited quark resonances decaying into qW (qZ) at 2.38 TeV (2.15 TeV) and upper limits are set on the cross section for resonances decaying to qW , qZ , WW , WZ , or ZZ final states.

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1. Introduction

New resonances that decay preferentially into hadronic final states are of particular interest in a variety of scenarios for physics beyond the standard model (SM) [1–9]. Searches for events having a pair of hadronic jets with large invariant mass have been performed by the Compact Muon Solenoid (CMS) and ATLAS experiments at the Large Hadron Collider (LHC) [10,11]. In principle, these searches are also sensitive to final states that include one or two massive vector bosons W/Z because the vector bosons have large hadronic branching fractions and because their masses are much smaller than those of the hypothetical parent states, i.e. they are highly “boosted”. This implies that the pairs of quark jets produced by the vector boson decays merge into single W/Z -jets in a real detector. Due to the large hadronic branching fractions of the vector bosons, at the highest accessible resonance masses, a search in the fully hadronic final state can be more sensitive than searches in leptonic channels. The sensitivity of the present large mass dijet searches is limited by the presence of background from ordinary strong interaction processes that produce pairs of quark and gluon jets.

The analysis presented here exploits the enhancement of the sensitivity of a standard dijet analysis for processes that produce W/Z -jets in the final state by the application of techniques

that can identify W/Z -jets and suppress quark and gluon jets (“ W/Z -tagging”). This CMS study is performed on pp collision data at a center-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 5.0 fb^{-1} . We consider events with two high-transverse-momentum jets in the final state. We identify “subjets” inside jets using recent developments in the area of jet substructure [12]. Pairs of subjets are used to explicitly reconstruct W or Z bosons, therefore substantially suppressing backgrounds from quantum chromodynamics (QCD) interactions. This search follows closely the procedures of the corresponding dijet search [10], performed in the same dataset, but with strongly reduced QCD background because of the W/Z -tagging.

We consider three benchmark scenarios that would produce singly or doubly tagged events: an excited quark q^* [4] decaying into a quark and a W or Z boson; a Randall–Sundrum (RS) graviton G_{RS} [13] decaying to WW or ZZ ; and a heavy partner of the SM W boson W' which decays to WZ [8]. The most stringent limits on the q^* model have been set in dijet resonance searches at the LHC by considering the qg final state [10] or inclusively all-hadronic final states [11]. The most stringent lower limit (at 95% CL) on the q^* mass to date is 3.3 TeV [10]. Specific searches for the qW and qZ final states have previously been reported at the Tevatron [14,15], which exclude resonances decaying to qW or qZ with masses up to 540 GeV, and at the LHC [16], which extends the mass exclusion of qZ resonances up to 1.94 TeV. For the G_{RS} , there are phenomenological models favoring the decay of the G_{RS} into vector bosons rather than photons or fermions [17–19]. In particular, the ZZ final state has been explored experimentally [20–22],

* E-mail address: cms-publication-committee-chair@cern.ch.

setting lower limits on the G_{RS} mass as a function of the coupling parameter k/\bar{M}_{Pl} , where k is the curvature of the warped space and \bar{M}_{Pl} the reduced Planck mass ($\bar{M}_{\text{Pl}} \equiv M_{\text{Pl}}/\sqrt{8\pi}$). For the W' , the most stringent limits are reported in searches with leptonic final states [23,24], and the current lower limit on the W' mass is 2.5 TeV. The limit varies by 0.1 TeV, depending on the chirality of the W' couplings. Specific searches in the WZ final state have also been reported [25,26] setting a lower limit of 1.1 TeV.

This Letter is organized as follows. First, the CMS detector, and the simulated and collision data samples on which the analysis is based are briefly described. Then the event reconstruction, and selection are detailed, and the W/Z-tagging technique is described. The following section describes the modeling of detector acceptances and signal efficiencies as well as the validation of the W/Z-tagging techniques with data. After this follows the description of the modeling of the background, the systematic uncertainties and the limit setting procedure. Finally the results and conclusions are presented.

2. CMS detector

The CMS detector [27] is well suited to the reconstruction of hadronic jets because it incorporates finely segmented electromagnetic and hadronic calorimeters, and a charged-particle tracking system. Charged particles are reconstructed in the inner tracker, which is immersed in a 3.8 T axial magnetic field. The inner tracker consists of three cylindrical layers and two endcap disks at each end of silicon pixel detectors, and ten barrel layers and twelve endcap disks at each end of silicon strip detectors. This arrangement results in full azimuthal coverage ($0 \leq \phi \leq 2\pi$) within $|\eta| < 2.5$, where η is the pseudorapidity defined as $\eta = -\ln[\tan(\theta/2)]$. CMS uses a polar coordinate system, with the z axis coinciding with the beam axis; θ is the polar angle defined with respect to the positive z axis. Muons are measured in gas-ionizing detectors embedded in the steel return yoke. A lead-tungstate crystal electromagnetic calorimeter (ECAL) up to $|\eta| = 3$ and a brass/scintillator hadronic calorimeter (HCAL) up to $|\eta| = 5$ surround the tracking volume and allow photon, electron, and jet reconstruction. The ECAL and HCAL cells are grouped into towers projecting radially outward from the interaction region. In the central region ($|\eta| < 1.74$) the towers have dimensions $\Delta\eta = \Delta\phi = 0.087$; at higher $|\eta|$, the $\Delta\eta$ and $\Delta\phi$ widths increase. For optimum jet reconstruction, the tracking and calorimeter information is combined in an algorithm called particle flow [28], which is described below.

3. Simulated and collision data samples

The sample of proton–proton collision data at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.0 fb^{-1} , was collected in 2011. The events were collected using the logical “or” of a set of triggers based on requirements on $H_{\text{T}} = \sum_{\text{jets}} p_{\text{T}}$ (p_{T} is the transverse momentum of a jet) and the invariant mass of the two highest p_{T} jets in an event, whose thresholds were raised progressively to cope with an increase in the peak luminosity during 2011.

Data are compared to Monte Carlo (MC) simulations of the QCD background generated using both PYTHIA 6.424 [29] and HERWIG++ 2.4.2 [30]. PYTHIA 6 is used with CTEQ61L [31] and HERWIG++ with MRST2001 [32] parton distribution functions. Tune Z2 (identical to tune Z1 [33] except that Z2 uses the CTEQ6L PDF while Z1 uses CTEQ5L) is used with PYTHIA 6, while the tune version 23 [30] is used with HERWIG++. In this analysis, the background shape is modeled from the data themselves. Therefore, the analysis depends on QCD simulation only to provide guidance and cross checks.

The sensitivity of the event selection to the benchmark processes is evaluated using simulated samples of events from excited

quarks, RS gravitons, and W' production and decay models. The process $qg \rightarrow q^* \rightarrow W/Z + \text{jet}$ is generated using PYTHIA 6 assuming the couplings to the SU(2), U(1) and SU(3) groups are $f = f' = f_s = 1$ for the production and decay of the q^* . The process $G_{\text{RS}} \rightarrow WW/ZZ$ is generated using HERWIG++ and its cross section is taken from PYTHIA 6. While HERWIG++ contains a more detailed description of the angular distributions than PYTHIA 6 for this process [34], the cross section is taken from PYTHIA 6 which has been used as a reference model in related analyses [20]. RS graviton production is studied with $k/\bar{M}_{\text{Pl}} = 0.1$, which determines a resonance width of about 1% of the resonance mass which is about a factor 5 smaller than the experimental resolution for dijets. This width is much smaller than suggested by the model in Ref. [17], which predicts resonance widths of the order of the experimental resolution, allowing for interpretation in this model only approximately. The process $W' \rightarrow WZ$ is generated using PYTHIA 6 with Standard Model $V-A$ couplings and without applying k -factors. All Monte Carlo events are passed through the CMS detector simulation based on GEANT4 [35].

4. Event reconstruction and selection

Events are reconstructed using the particle flow algorithm, which attempts to identify and measure all the stable particles in a collision by combining information from all the subdetectors. This algorithm categorizes all particles into five types: muons, electrons, photons, charged and neutral hadrons. The resulting particle flow candidates are passed to the anti- k_{T} [36] and Cambridge–Aachen (CA) [37,38] jet clustering algorithms, as implemented in FASTJET [39,40] to create jets. A distance parameter of size $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.8$ is used for the CA algorithm, while $R = 0.5$ is used for the anti- k_{T} algorithm. While the anti- k_{T} jets are used to select events and reconstruct the dijet invariant mass m_{jj} , the CA jets are used to identify events containing hadronically decaying W or Z bosons. This choice has been made because the CA algorithm was found to be more efficient (for the same mistag rate) at finding hard subjets within the jets in simulation-based studies [12], while the anti- k_{T} jets have the best energy calibration.

Events must have at least one reconstructed vertex within $|z| < 15$ cm, to suppress backgrounds solely triggered by calorimeter noise. The primary vertex is defined as the vertex with highest sum of squared track transverse momenta (p_{T}^2). Charged particles not originating from it are removed from the inputs to the jet clustering algorithms. This requirement removes particles which arise from additional pp interactions in the same pp bunch crossing (pileup interactions). An event-by-event jet-area-based correction [41–43] is applied to remove the remaining pileup energy which is due to neutral particles originating from the other vertices. The pileup-subtracted jet four momenta are finally corrected to account for the difference between the measured and true responses to hadrons [43]. When jets are decomposed into subjets, as described later, the energy estimate relies on the calibrated reconstructed input particles without further corrections.

Events are initially selected by requiring that they have at least two anti- k_{T} jets with $p_{\text{T}} > 30$ GeV and $|\eta| < 2.5$. The two highest- p_{T} jets are required to have a pseudorapidity separation $|\Delta\eta| < 1.3$ to reduce the QCD dijet background [44]. Finally, the dijet invariant mass is required to be larger than 890 GeV. This threshold is defined by the triggers, which were found to be 99% efficient for dijet events with masses above this threshold.

In events passing this selection, “boosted” (high p_{T}) hadronically decaying W or Z bosons are identified with a W/Z-tagging algorithm using jet pruning [45], a technique which removes the softest components of the jets. In the jet pruning technique [46,47], a jet is reclustered using all the particles used to build

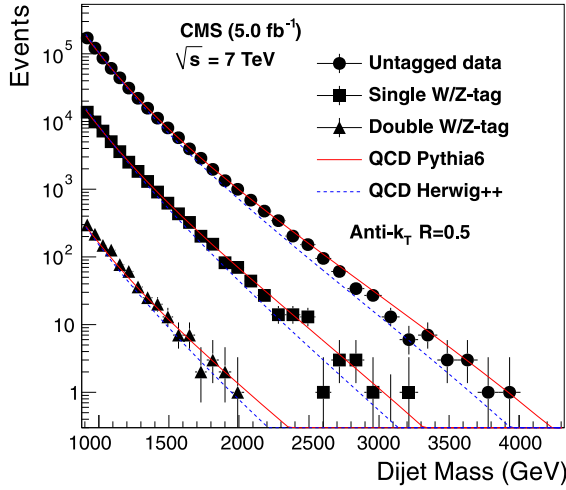


Fig. 1. Comparisons of the dijet invariant mass distributions between data and Monte Carlo (PYTHIA 6 and HERWIG++) simulations. The three sets of lines correspond to the inclusive dijet category (no W/Z-tag required), single W/Z-tagged, and double W/Z-tagged events. The simulations are normalized to the number of data events in each category.

a CA jet, ignoring in each recombination step the softer “protojet” if the recombination is softer than a given threshold $z_{\text{cut}} = 0.1$ or forms an angle ΔR wider than $D_{\text{cut}} = 0.5m_{\text{T}}^{\text{orig}}/p_{\text{T}}^{\text{orig}}$ with respect to the previous recombination step, where $m_{\text{T}}^{\text{orig}}$ and $p_{\text{T}}^{\text{orig}}$ are the mass and transverse momentum of the original CA jet. The hardness of a recombination z is defined as $z = \min(p_{\text{T}}^i, p_{\text{T}}^j)/p_{\text{T}}^p$, where p_{T}^i and p_{T}^j are the p_{T} of the two protojets to be combined and p_{T}^p is the p_{T} of the combined jet. The following selection is then applied to the pruned jets to identify jets from hadronic W/Z decays by exploiting the variables used in Ref. [48]. The total pruned jet mass m_{jet} must satisfy $70 \text{ GeV} < m_{\text{jet}} < 100 \text{ GeV}$. Two subjets are obtained by undoing the last clustering iteration of the pruned jet clustering. The ratio of masses of the highest mass subjet (m_1) and the total pruned jet mass is defined as the *mass drop* $\frac{m_1}{m_{\text{jet}}}$. To discriminate against QCD jets, the mass drop is required to satisfy $\frac{m_1}{m_{\text{jet}}} < 0.25$. These criteria are designed to select W and Z candidates in which the subjets are similar in energy and mass.

Comparisons of the dijet invariant mass distributions for untagged, single-tagged, and double-tagged event samples are shown in Fig. 1. The data are shown as solid points and the PYTHIA 6 and HERWIG++ simulations are shown as solid red and dashed blue curves, respectively. The simulations are normalized to the number of data events in each category and the shapes are compared; the agreement of the normalization driven by the W/Z-tagging efficiency is discussed in the next section. The PYTHIA 6 prediction is found to agree with the data while the HERWIG++ prediction decreases more steeply with mass. However, no systematic uncertainties are taken into account and only the dominant background from QCD interactions is considered.

5. Signal characterization

A search for dijet resonances corresponding to several benchmark physics models is performed. Using the W/Z-tagging algorithm, both single W/Z-tag and double W/Z-tag events are examined. The signals that would be produced by the benchmark physics models have different characteristics that are described below.

The pruned jet mass and mass drop distributions in data, signal, and background simulations are shown in Fig. 2. The discriminat-

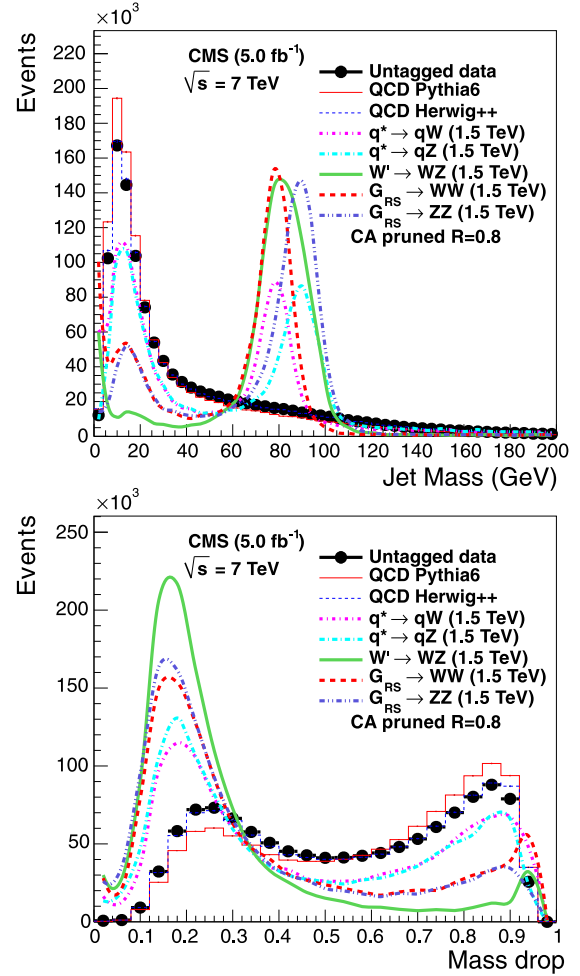


Fig. 2. Pruned jet mass (top) and mass drop (bottom) in data, signal and background simulations. The signal simulation distributions are plotted as smooth curves connecting the histogram entries (using the same binning as the data distribution). All simulation distributions have been scaled to match the number of data events.

ing power of the pruned jet mass and mass drop for the different signals is evident. In both the pruned jet mass and the mass drop distributions, small differences may be seen between the results obtained with HERWIG++ (WW, ZZ) and PYTHIA 6 (WZ, qW, qZ), which arise from differences in the showering and hadronization models used by these generators. This effect is taken into account in the estimate of the systematic uncertainties on the tagging efficiency, as described below.

The acceptance, defined as the product of signal branching fraction into dijet final states $B(W/Z \rightarrow \text{jets})$ times angular acceptance ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$), is shown in Fig. 3. Each model relevant for the singly (doubly) tagged data analysis is shown in the dijet invariant mass range up to 2 TeV (3 TeV). The fraction of events that produce dijet events, which have survived the kinematic selection, is between 26% and 47%. This fraction includes also the branching fraction of W/Z decaying into objects which are reconstructed as jets. The different behavior of the acceptance for W' and G_{RS} at low dijet masses is due to different angular distributions generated by PYTHIA 6 and HERWIG++.

The W/Z-tagging efficiency, which is not part of the acceptance, is shown for signal and background events in Fig. 4. The signal efficiency, determined from the simulation, is found to be between 20% and 45% (8% and 22%) for single (double) W/Z-tagged signals. The W-tagging efficiency is larger than the Z-tagging efficiency due to the choice of the jet mass window cut, which rejects a larger

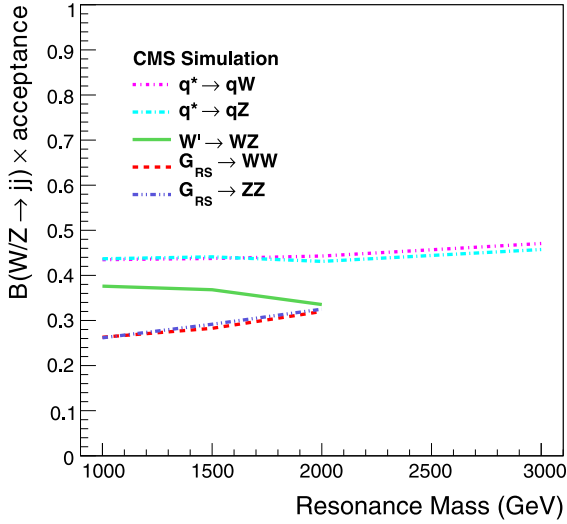


Fig. 3. The branching fraction into dijet final states $B(W/Z \rightarrow \text{jets})$ times angular acceptance ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$). The W/Z-tagging efficiencies are excluded from the acceptance.

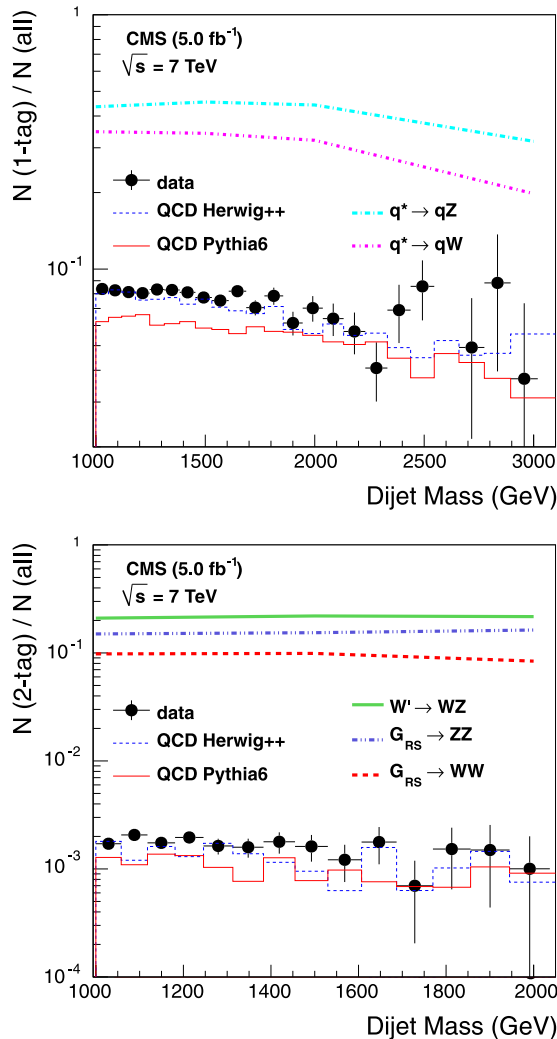


Fig. 4. Efficiency of requiring 1 W/Z-tag (top) and 2 W/Z-tags (bottom) in signal and background simulations, and in data for events passing the angular acceptance requirement ($|\eta| < 2.5$, $|\Delta\eta| < 1.3$).

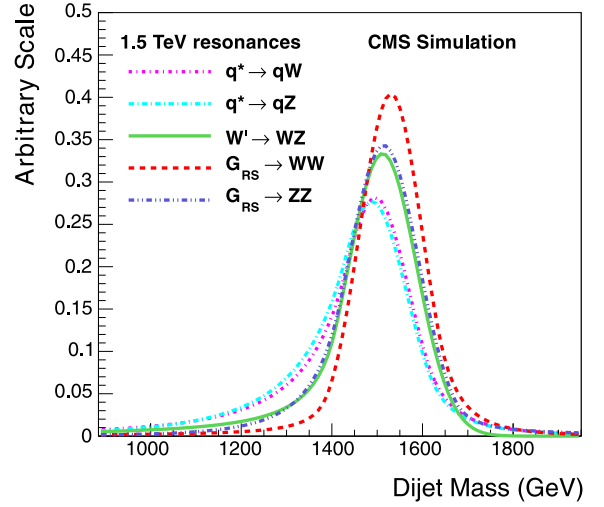


Fig. 5. The signal dijet invariant mass distributions for 1.5 TeV $G_{RS} \rightarrow WW$, $G_{RS} \rightarrow ZZ$, $W' \rightarrow WZ$, $q^* \rightarrow qW$, and $q^* \rightarrow qZ$ resonances, computed using anti- k_T jets with $R = 0.5$. Crystal-Ball functions fit to the simulated distributions are shown. The distributions in the plot are scaled to the same integral.

fraction of W bosons by requiring $m_{\text{jet}} > 70$ GeV. The simulation modeling of the signal efficiency is cross-checked by measuring the W/Z-tagging efficiency in semileptonic $t\bar{t}$ data and by comparing it with the same efficiency obtained using the same procedure for $t\bar{t}$ simulation generated with MADGRAPH 4.4.12 [49] and showered with PYTHIA 6. We follow the same procedure as described in Ref. [50]. The ratio of the two efficiencies results in a scale factor of 0.98 ± 0.03 which is then applied to the efficiencies for signals in the dijet data. The uncertainties on the scale factor are propagated into the systematic uncertainties on the overall signal efficiency.

As described above, the production and decay of the G_{RS} is modeled with HERWIG++. A difference of up to 18% on the double-tag efficiency in the RS graviton WW/ZZ signal simulations between PYTHIA 6 and HERWIG++ is observed. The difference can be attributed in equal parts to the different showering algorithms and the hadronization algorithms. The different underlying event modeling has only a small impact of $< 1\%$. This discrepancy is accounted for as a systematic uncertainty on the double-tag efficiency. For the single-tag efficiency a 9% uncertainty is assigned based on the double-tag efficiency uncertainty of 18% assuming an identical difference in tagging efficiency for the two vector bosons in the case of 100% efficiency, representing an upper limit on this uncertainty.

The effect of pileup on the W/Z-tagging efficiency was also checked. Because of the rejection of charged particles not originating from the primary vertex and the application of pruning, the pileup dependence is weak and the uncertainty of the modeling of the pileup distribution is less than 2%.

The dijet mass dependence of the W/Z-tagging efficiency for background events shown in Fig. 4 is adequately described by the simulation. Therefore, no additional systematic uncertainty is assigned on the dijet mass dependence of the modeling of the W/Z-tagging in simulation.

Fig. 5 shows the signal shapes for $G_{RS} \rightarrow ZZ/WW$, $W' \rightarrow WZ$, and $q^* \rightarrow qW/qZ$, all of which correspond to a resonance mass of 1.5 TeV. The differences for the different models are to a large extent due to the different tagging efficiencies for W and Z and to a smaller extent to differences in the models in PYTHIA 6 and HERWIG++. The lower cut of 70 GeV on the jet mass in the W/Z-tag biases the resonance peak for WW, WZ and qW towards higher masses, especially when two tags are applied on the WW sample.

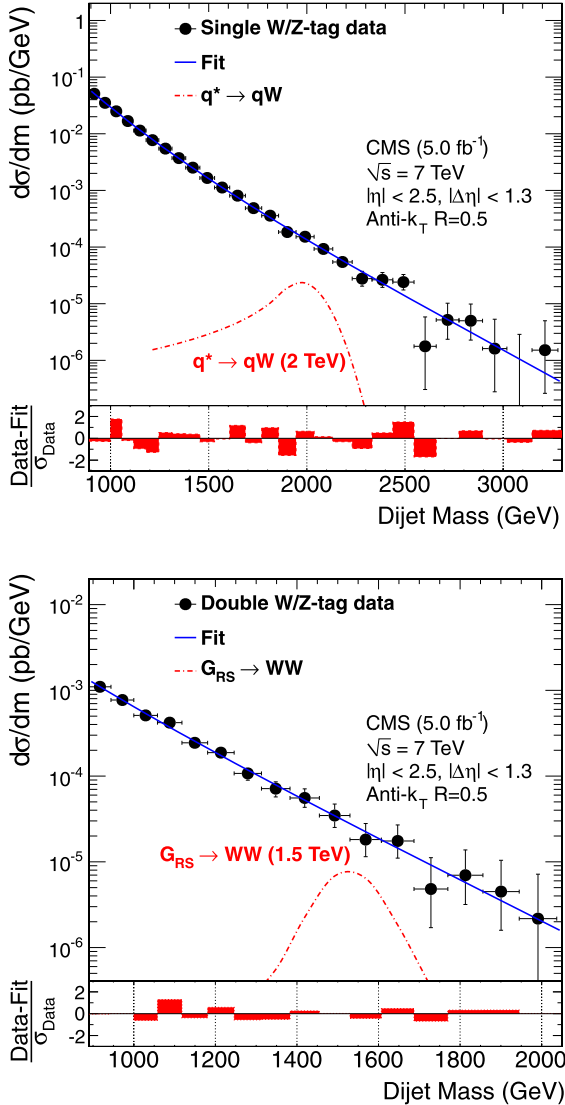


Fig. 6. The single (top) and double (bottom) W/Z-tagged m_{jj} distributions (points) in data fitted with the QCD background parametrization (solid curve). For the double W/Z-tagged distribution $P_3 = 0$ is assumed in Eq. (1). Signal shape distributions for $q^* \rightarrow qW$ and $G_{RS} \rightarrow WW$ with arbitrary cross sections are also shown. The bottom panes show the corresponding pull distributions ($\frac{\text{Data-Fit}}{\sigma_{\text{Data}}}$). There are no data events with dijet masses larger than the range of these plots.

We have checked that this behavior is reproduced in both PYTHIA 6 and HERWIG++. The difference in resolution between the singly tagged and doubly tagged resonance shapes is also due to this bias of the extra W/Z-tag requirement. Resonance shapes were simulated at masses of 1, 1.5, 2 and 3 TeV and a linear interpolation was used to obtain the shapes at intermediate masses.

6. Background shape parametrization

The shape of the QCD background in the dijet spectrum is modeled using a simple parametrization which has been successfully deployed in previous searches [51]. The background model is given by:

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3} \ln(m/\sqrt{s})}, \quad (1)$$

where m denotes the dijet mass and \sqrt{s} the pp center of mass energy. P_0 acts as a normalization parameter for the probability

density function, and P_1, P_2, P_3 describe its shape. For the single W/Z-tagged analysis, all parameters are free to float in the fit. For the double W/Z-tagged analysis, P_3 is not needed as suggested by a Fisher F-test [52] and a simpler parametrization with P_3 fixed to 0 is used.

Fig. 6 shows the dijet mass spectra from single and double W/Z-tagged data fitted to Eq. (1) and the corresponding pull distributions, demonstrating the agreement between the background-only probability density function and the data.

Since no sizable deviation from the background-only hypothesis is seen, exclusion limits are set on the product of cross section, acceptance, and branching fraction for the five considered final states: qW , qZ , WW , WZ , and ZZ .

7. Systematic uncertainties

The sources of systematic uncertainties are summarized as follows. The only background-related systematic uncertainty is the choice of background parametrization which is discussed in Section 8. The leading signal-related systematic uncertainties are the W/Z-tagging efficiency (Section 5), jet energy scale (JES), jet energy resolution (JER), and luminosity measurement. Because the trigger and reconstruction efficiencies are larger than 99% in the relevant dijet mass range, the uncertainties associated with these efficiencies are negligible.

In the jet p_T - and η -regions considered in this analysis, the JES has an uncertainty of 2–3% [43]. The p_T - and η -dependent uncertainty is propagated to an uncertainty on the reconstructed dijet invariant mass of 2.2%, which is approximately mass independent. The effect of the JES uncertainty on the calculation of the limits is estimated by varying the resonance dijet mass in the statistical analysis. The JER is known to a precision of 10% and its tails are in agreement between data and simulation [43]. The effect of the JER uncertainty on the calculation of the limits is estimated by varying the reconstructed resonance width in the statistical analysis. The luminosity has an uncertainty of 2.2% [53], which is also taken into account in the statistical analysis.

8. Limit setting procedure

For setting upper limits on the resonance production cross section a Bayesian formalism with uniform prior for the cross section is used, following the procedure used in Ref. [51]. The binned likelihood, L , can be written as:

$$L = \prod_i \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}, \quad (2)$$

where

$$\mu_i = \alpha N_i(S) + N_i(B), \quad (3)$$

n_i is the observed number of events in the i th dijet mass bin, $N_i(S)$ is the expected number of events from the signal in the i th dijet mass bin, α scales the signal amplitude, and $N_i(B)$ is the expected number of events from background in the i th dijet mass bin. The background $N_i(B)$ is estimated as the background component of the best 5(4)-parameter fit of Eq. (3) to the singly (doubly) tagged data points. The signal is not restricted to be positive for the background estimate fit although it is restricted in the Bayesian prior for the signal. A flat prior in α , which is the same as a flat prior in the resonance production cross section, is assumed.

The dominant sources of systematic uncertainty (the jet energy scale, the jet energy resolution, the integrated luminosity, and the W/Z-tagging efficiency) are considered as nuisance parameters associated to log-normal priors. The uncertainty on the background

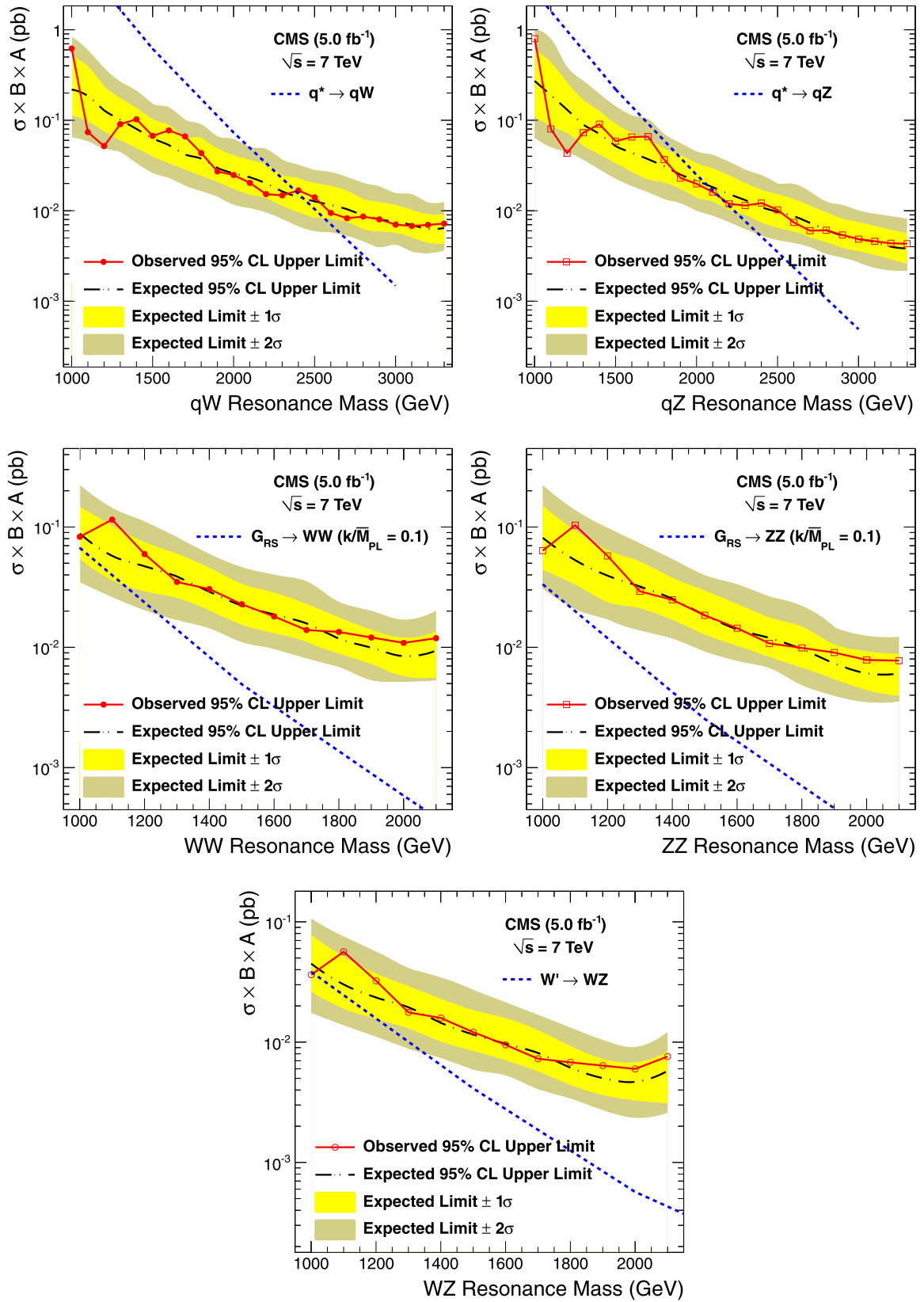


Fig. 7. Expected and observed limits for qW (top-left), qZ (top-right), WW (center-left), ZZ (center-right) and WZ (bottom) resonances. Here, $B \times A$ in the vertical axis label contains the branching fraction of $G_{RS} \rightarrow WW/ZZ \rightarrow 2$ jets or $q^* \rightarrow qW/qZ \rightarrow 2$ jets, as well as the acceptance for reconstructing the jets in $|\eta| < 2.5$, $|\Delta\eta| < 1.3$. The predicted cross sections as a function of resonance mass for the considered benchmark models are overlaid.

shape is taken into account with nuisance parameters associated to Gaussian priors representing variations of the fit parameters along the eigenvectors of their correlation matrix. The systematic uncertainties are accounted for using a fully Bayesian treatment and integrating the likelihood over nuisance parameters.

The 95% confidence level (CL) upper limit σ_S is calculated from the normalized posterior probability density P_{post} as follows:

$$\int_0^{\sigma_S} P_{\text{post}}(\sigma) d\sigma = 0.95. \quad (4)$$

This method of using the data first to constrain the background fit and second to extract the limit induces a bias in the coverage of the limits. The actual coverage is reduced to 93.6% (94.3%) at a WW (qW) signal mass of 1200 GeV (1800 GeV).

9. Results

Fig. 7 shows the 95% CL cross section upper limits derived from the single and double W/Z-tagged event samples. The predicted cross sections as a function of resonance mass for the considered benchmark models are overlaid. A 95% CL lower limit is set on the mass of excited quark resonances decaying into qW (qZ) at 2.38 TeV (2.15 TeV), whereas a limit of 2.43 TeV (2.07 TeV) is expected. These are the most stringent limits in the qW and qZ final states to date. The sensitivity of our measurement with the present dataset is not sufficient to extract substantive mass limits on the G_{RS} with $k/\overline{M}_{Pl} = 0.1$ nor the heavy SM-like W' boson, but the cross section limits are the most stringent in the fully hadronic final state to date. Comparing to the cross section limits on G_{RS} decays to ZZ in the corresponding semileptonic final states [20–22], this analysis sets a stronger cross section limit above a G_{RS} mass of roughly 1.4 TeV. The cross section limits on final states with ZZ are stronger than those with WW because the efficiency for tagging a Z is larger than that for a W. The predicted cross section for WW is twice as large as for ZZ in the G_{RS} model because of charge-conjugation.

The dominant source of systematic uncertainty is the jet energy scale. Removing all systematic uncertainties on the single and double tagged searches would decrease the upper limit on the cross section by less than 20% at all values of resonance mass, which would translate into a change on resonances mass limits of roughly 3%.

10. Summary

A data sample corresponding to an integrated luminosity of 5.0 fb^{-1} collected in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ with the CMS detector was used to measure the W/Z-tagged dijet mass spectrum using the two leading jets within the pseudorapidity range $|\eta| < 2.5$ and with pseudorapidity separation $|\Delta\eta| < 1.3$. By suppressing the QCD background with the selection of candidates for vector bosons decaying to hadrons within jets, no evidence was found for new particle production in the W/Z-tagged dijet spectrum. A 95% CL lower limit is set on the mass of excited quark resonances decaying into qW (qZ) at 2.38 TeV (2.15 TeV) and upper limits on the cross section for resonances decaying to qW, qZ, WW, WZ, or ZZ final states. These are the most stringent limits in the qW and qZ final states to date.

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References

- [1] L.A. Anchordoqui, H. Goldberg, S. Nawata, T.R. Taylor, Phys. Rev. Lett. 100 (2008) 171603, <http://dx.doi.org/10.1103/PhysRevLett.100.171603>, arXiv:0712.0386.
- [2] S. Cullen, M. Perelstein, M.E. Peskin, Phys. Rev. D 62 (2000) 055012, <http://dx.doi.org/10.1103/PhysRevD.62.055012>, arXiv:hep-ph/0001166.
- [3] J.L. Hewett, T.G. Rizzo, Phys. Rept. 183 (1989) 193, [http://dx.doi.org/10.1016/0370-1573\(89\)90071-9](http://dx.doi.org/10.1016/0370-1573(89)90071-9).
- [4] U. Baur, I. Hinchliffe, D. Zeppenfeld, Int. J. Mod. Phys. A 2 (1987) 1285, <http://dx.doi.org/10.1142/S0217751X87000661>.
- [5] U. Baur, M. Spira, P.M. Zerwas, Phys. Rev. D 42 (1990) 815, <http://dx.doi.org/10.1103/PhysRevD.42.815>.
- [6] P.H. Frampton, S.L. Glashow, Phys. Lett. B 190 (1987) 157, [http://dx.doi.org/10.1016/0370-2693\(87\)90859-8](http://dx.doi.org/10.1016/0370-2693(87)90859-8).
- [7] E.H. Simmons, Phys. Rev. D 55 (1997) 1678, <http://dx.doi.org/10.1103/PhysRevD.55.1678>, arXiv:hep-ph/9608269.
- [8] E. Eichten, I. Hinchliffe, K. Lane, C. Quigg, Rev. Mod. Phys. 56 (1984) 579, <http://dx.doi.org/10.1103/RevModPhys.56.579>.
- [9] L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690, <http://dx.doi.org/10.1103/PhysRevLett.83.4690>.
- [10] CMS Collaboration, JHEP 1301 (2013) 013, [http://dx.doi.org/10.1007/JHEP01\(2013\)013](http://dx.doi.org/10.1007/JHEP01(2013)013), arXiv:1210.2387.
- [11] ATLAS Collaboration, JHEP 1301 (2013) 029, [http://dx.doi.org/10.1007/JHEP01\(2013\)029](http://dx.doi.org/10.1007/JHEP01(2013)029), arXiv:1210.1718.
- [12] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-JME-09-001 (2009), <http://cdsweb.cern.ch/record/1194489>.
- [13] L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370, <http://dx.doi.org/10.1103/PhysRevLett.83.3370>, arXiv:hep-ph/9905221.
- [14] CDF Collaboration, F. Abe, et al., Phys. Rev. Lett. 72 (1994) 3004, <http://dx.doi.org/10.1103/PhysRevLett.72.3004>.
- [15] D0 Collaboration, V.M. Abazov, et al., D0, Phys. Rev. D 74 (2006) 011104, <http://dx.doi.org/10.1103/PhysRevD.74.011104>, arXiv:hep-ex/0606018.
- [16] CMS Collaboration, Phys. Lett. B 722 (2013) 28, <http://dx.doi.org/10.1016/j.physletb.2013.03.037>, arXiv:1210.0867.
- [17] K. Agashe, H. Davoudiasl, G. Perez, A. Soni, Phys. Rev. D 76 (2007) 036006, <http://dx.doi.org/10.1103/PhysRevD.76.036006>, arXiv:hep-ph/0701186.
- [18] O. Antipin, D. Atwood, A. Soni, Phys. Lett. B 666 (2008) 155, <http://dx.doi.org/10.1016/j.physletb.2008.07.009>, arXiv:0711.3175.
- [19] O. Antipin, A. Soni, JHEP 0810 (2008) 018, <http://dx.doi.org/10.1088/1126-6708/2008/10/018>, arXiv:0806.3427.
- [20] CMS Collaboration, Phys. Lett. B 718 (2013) 1208, <http://dx.doi.org/10.1016/j.physletb.2012.11.063>, arXiv:1209.3807.

- [21] ATLAS Collaboration, Phys. Lett. B 712 (2012) 331, <http://dx.doi.org/10.1016/j.physletb.2012.05.020>, arXiv:1203.0718.
- [22] CDF Collaboration, T. Aaltonen, et al., Phys. Rev. D 85 (2012) 012008, <http://dx.doi.org/10.1103/PhysRevD.85.012008>, arXiv:1111.3432.
- [23] CMS Collaboration, JHEP 1208 (2012) 023, [http://dx.doi.org/10.1007/JHEP08\(2012\)023](http://dx.doi.org/10.1007/JHEP08(2012)023).
- [24] ATLAS Collaboration, Phys. Lett. B 705 (2011) 28, <http://dx.doi.org/10.1016/j.physletb.2011.09.093>, arXiv:1108.1316.
- [25] CMS Collaboration, Phys. Rev. Lett. 109 (2012) 141801, <http://dx.doi.org/10.1103/PhysRevLett.109.141801>.
- [26] ATLAS Collaboration, Phys. Rev. D 85 (2012) 112012, <http://dx.doi.org/10.1103/PhysRevD.85.112012>, arXiv:1204.1648.
- [27] CMS Collaboration, JINST 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [28] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-PFT-09-001 (2009), <http://cdsweb.cern.ch/record/1194487>.
- [29] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [30] M. Bähr, S. Gieseke, M.A. Gigg, D. Grellscheid, K. Hamilton, O. Latunde-Dada, S. Plätzer, P. Richardson, M.H. Seymour, A. Sherstnev, B.R. Webber, Eur. Phys. J. C 58 (2008) 639, <http://dx.doi.org/10.1140/epjc/s10052-008-0798-9>, arXiv:0803.0883.
- [31] J. Pumplin, D.R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, W.-K. Tung, JHEP 0207 (2002) 012, <http://dx.doi.org/10.1088/1126-6708/2002/07/012>, arXiv:hep-ph/0201195.
- [32] A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, Eur. Phys. J. C 23 (2002) 73, <http://dx.doi.org/10.1007/s100520100842>, arXiv:hep-ph/0110215.
- [33] R. Field, Early LHC underlying event data – findings and surprises, in: Proceedings of the Hadron Collider Physics Symposium, 2010, <http://arxiv.org/abs/1010.3558>, arXiv:1010.3558.
- [34] CMS Collaboration, Search for Randall–Sundrum graviton excitations in the CMS experiment, <http://arxiv.org/abs/hep-ex/0207061>, arXiv:hep-ex/0207061, 2002.
- [35] S. Agostinelli, et al., GEANT4, Nucl. Instrum. Meth. A 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [36] M. Cacciari, G.P. Salam, G. Soyez, JHEP 0804 (2008) 063, <http://dx.doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [37] M. Wobisch, T. Wengler, Hadronization corrections to jet cross sections in deep-inelastic scattering, <http://arxiv.org/abs/hep-ph/9907280>, arXiv:hep-ph/9907280, 1998.
- [38] Y.L. Dokshitzer, G.D. Leder, S. Moretti, B.R. Webber, JHEP 9708 (1997) 001, <http://dx.doi.org/10.1088/1126-6708/1997/08/001>, arXiv:hep-ph/9707323.
- [39] M. Cacciari, G.P. Salam, Phys. Lett. B 641 (2006) 57, <http://dx.doi.org/10.1016/j.physletb.2006.08.037>, arXiv:hep-ph/0512210.
- [40] M. Cacciari, G.P. Salam, G. Soyez, Eur. Phys. J. C 72 (2012) 1896, <http://dx.doi.org/10.1140/epjc/s10052-012-1896-2>, arXiv:1111.6097.
- [41] M. Cacciari, G.P. Salam, G. Soyez, JHEP 0804 (2008) 005, <http://dx.doi.org/10.1088/1126-6708/2008/04/005>, arXiv:0802.1188.
- [42] M. Cacciari, G.P. Salam, Phys. Lett. B 659 (2008) 119, <http://dx.doi.org/10.1016/j.physletb.2007.09.077>, arXiv:0707.1378.
- [43] CMS Collaboration, JINST 6 (2011) P11002, <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>.
- [44] CMS Collaboration, Phys. Lett. B 704 (2011) 123, <http://dx.doi.org/10.1016/j.physletb.2011.09.015>.
- [45] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-JME-10-013 (2010), <http://cdsweb.cern.ch/record/1333700>.
- [46] S.D. Ellis, C.K. Vermilion, J.R. Walsh, Phys. Rev. D 80 (2009) 051501, <http://dx.doi.org/10.1103/PhysRevD.80.051501>, arXiv:0903.5081.
- [47] S.D. Ellis, C.K. Vermilion, J.R. Walsh, Phys. Rev. D 81 (2010) 094023, <http://dx.doi.org/10.1103/PhysRevD.81.094023>, arXiv:0912.0033.
- [48] J.M. Butterworth, A.R. Davison, M. Rubin, G.P. Salam, Phys. Rev. Lett. 100 (2008) 242001, <http://dx.doi.org/10.1103/PhysRevLett.100.242001>, arXiv:0802.2470.
- [49] J. Alwall, P. Demin, S. de Visscher, R. Frederix, M. Herquet, F. Maltoni, T. Plehn, D.L. Rainwater, T. Stelzer, JHEP 0709 (2007) 028, <http://dx.doi.org/10.1088/1126-6708/2007/09/028>, arXiv:0706.2334.
- [50] CMS Collaboration, JHEP 1209 (2012) 029, [http://dx.doi.org/10.1007/JHEP09\(2012\)029](http://dx.doi.org/10.1007/JHEP09(2012)029), arXiv:1204.2488.
- [51] CMS Collaboration, Phys. Lett. B 704 (2011) 123, <http://dx.doi.org/10.1016/j.physletb.2011.09.015>, arXiv:1107.4771.
- [52] R.G. Lomax, D.L. Hahs-Vaughn, Statistical Concepts: A Second Course, Routledge Academic, 2007, p. 10.
- [53] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-SMP-12-008 (2012), <http://cdsweb.cern.ch/record/1434360>.

CMS Collaboration

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

T.S. Anjos^b, C.A. Bernardes^b, F.A. Dias^{a,3}, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, C. Lagana^a, F. Marinho^a, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

^a *Universidade Estadual Paulista, Sao Paulo, Brazil*

^b *Universidade Federal do ABC, Sao Paulo, Brazil*

V. Genchev⁴, P. Iaydjiev⁴, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina⁵, D. Polic, I. Puljak⁴

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran⁶, S. Elgammal⁷, A. Ellithi Kamel⁸, M.A. Mahmoud⁹, A. Radi^{10,11}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹², C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram¹³, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹³, F. Drouhin¹³, C. Ferro, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

F. Fassi, D. Mercier

Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici⁴, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Z. Tsamalaidze¹⁴

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

G. Anagnostou, C. Autermann, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber,

B. Wittmer, V. Zhukov¹⁵

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann⁴, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁶, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁶, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁶, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille¹⁷, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁴, C. Hackstein, F. Hartmann, T. Hauth⁴, M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov¹⁵, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

Institute of Nuclear Physics “Demokritos”, Aghia Paraskevi, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

J. Karacsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shrivastava

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁴, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECP, Mumbai, India

H. Arfaei²², H. Bakhshiansohi, S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁴, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,4}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,4}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti^{a,b}, G. Zito^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b,4}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,4}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, R. Travaglini^{a,b}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁵, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbriatore^a, R. Musenich^a, S. Tosi^{a,b}

^a *INFN Sezione di Genova, Genova, Italy*

^b *Università di Genova, Genova, Italy*

A. Benaglia^{a,b}, F. De Guio^{a,b}, L. Di Matteo^{a,b,4}, S. Fiorendi^{a,b}, S. Gennai^{a,4}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,4}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

^a *INFN Sezione di Milano-Bicocca, Milano, Italy*

^b *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo^a, C.A. Carrillo Montoya^a, N. Cavallo^{a,26}, A. De Cosa^{a,b,4}, O. Dogangun^{a,b}, F. Fabozzi^{a,26}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,27}, M. Merola^a, P. Paolucci^{a,4}

^a *INFN Sezione di Napoli, Napoli, Italy*

^b *Università di Napoli "Federico II", Napoli, Italy*

P. Azzi^a, N. Bacchetta^{a,4}, D. Bisello^{a,b}, A. Branca^{a,b,4}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

^a *INFN Sezione di Padova, Padova, Italy*

^b *Università di Padova, Padova, Italy*

^c *Università di Trento (Trento), Padova, Italy*

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

^a *INFN Sezione di Pavia, Pavia, Italy*

^b *Università di Pavia, Pavia, Italy*

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b,†}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}, S. Taroni^{a,b}

^a *INFN Sezione di Perugia, Perugia, Italy*

^b *Università di Perugia, Perugia, Italy*

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c,4}, R. Dell'Orso^a, F. Fiori^{a,b,4}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,28}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,29}, P. Spagnolo^a, P. Squillacioti^{a,4}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a *INFN Sezione di Pisa, Pisa, Italy*

^b *Università di Pisa, Pisa, Italy*

^c *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, C. Fanelli^{a,b}, M. Grassi^{a,b,4}, E. Longo^{a,b}, P. Meridiani^{a,4}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, M. Sigamani^a, L. Soffi^{a,b}

^a *INFN Sezione di Roma, Roma, Italy*

^b *Università di Roma, Roma, Italy*

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, N. Demaria^a, C. Mariotti^{a,4}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,4}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b},

A. Staiano^a, A. Vilela Pereira^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale (Novara), Torino, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,4},
D. Montanino^{a,b,4}, A. Penzo^a, A. Schizzi^{a,b}

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S.G. Heo, T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Kyungpook National University, Daegu, Republic of Korea

J.Y. Kim, Zero J. Kim, S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

Korea University, Seoul, Republic of Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Vilnius University, Vilnius, Lithuania

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba,
J. Martínez-Ortega, A. Sanchez-Hernandez, L.M. Villasenor-Cendejas

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

University of Canterbury, Christchurch, New Zealand

M. Ahmad, M.H. Ansari, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Bunin, M. Gavrilenko, I. Golutvin, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, A. Volodko, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrillov, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin³, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin, A. Snigirev

Moscow State University, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin⁴, V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic³⁰, M. Djordjevic, M. Ekmedzic, D. Krpic³⁰, J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³¹, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC - Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet⁵, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³², C. Rovelli³³, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁴, D. Spiga, A. Tsirou, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁵, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁶, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov³⁷, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler³⁸, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas

Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar⁴¹, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴², A. Polatoz, K. Sogut⁴³, D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, L.N. Vergili, M. Vergili

Cukurova University, Adana, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak⁴⁴, M. Kaya⁴⁵, O. Kaya⁴⁵, S. Ozkorucuklu⁴⁶, N. Sonmez⁴⁷

Bogazici University, Istanbul, Turkey

K. Cankocak

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁵, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso⁴⁸, K.W. Bell, A. Belyaev⁴⁸, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³⁷, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁴⁹, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

University of California, Davis, Davis, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], P. Traczyk, V. Valuev, M. Weber

University of California, Los Angeles, Los Angeles, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵⁰, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵¹, F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

University of California, Santa Barbara, Santa Barbara, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luigi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Cornell University, Ithaca, USA

D. Winn*Fairfield University, Fairfield, USA*

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵², C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵³, G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

Florida Institute of Technology, Melbourne, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

University of Illinois at Chicago (UIC), Chicago, USA

U. Akgun, E.A. Albayrak, B. Bilki⁵⁴, W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya⁵⁵, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok⁵⁶, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

The University of Kansas, Lawrence, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, M. Boutemur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar⁵⁷, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

Massachusetts Institute of Technology, Cambridge, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar

State University of New York at Buffalo, Buffalo, USA

G. Alverson^{*}, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

A. Anastassov, A. Kubik, L. Lusito, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

Northwestern University, Evanston, USA

L. Antonelli, D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

University of Notre Dame, Notre Dame, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

The Ohio State University, Columbus, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

University of Rochester, Rochester, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Duder, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

Wayne State University, Detroit, USA

M. Anderson, D.A. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

University of Wisconsin, Madison, USA

* Corresponding author.

E-mail address: George.Alverson@cern.ch (G. Alverson).

† Deceased.

- ¹ Also at Vienna University of Technology, Vienna, Austria.
- ² Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
- ³ Also at California Institute of Technology, Pasadena, USA.
- ⁴ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ⁵ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.
- ⁶ Also at Suez Canal University, Suez, Egypt.
- ⁷ Also at Zewail City of Science and Technology, Zewail, Egypt.
- ⁸ Also at Cairo University, Cairo, Egypt.
- ⁹ Also at Fayoum University, El-Fayoum, Egypt.
- ¹⁰ Also at British University in Egypt, Cairo, Egypt.
- ¹¹ Now at Ain Shams University, Cairo, Egypt.
- ¹² Also at National Centre for Nuclear Research, Swierk, Poland.
- ¹³ Also at Université de Haute-Alsace, Mulhouse, France.
- ¹⁴ Also at Joint Institute for Nuclear Research, Dubna, Russia.
- ¹⁵ Also at Moscow State University, Moscow, Russia.
- ¹⁶ Also at Brandenburg University of Technology, Cottbus, Germany.
- ¹⁷ Also at The University of Kansas, Lawrence, USA.
- ¹⁸ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ¹⁹ Also at Eötvös Loránd University, Budapest, Hungary.
- ²⁰ Also at Tata Institute of Fundamental Research - HECR, Mumbai, India.
- ²¹ Also at University of Visva-Bharati, Santiniketan, India.
- ²² Also at Sharif University of Technology, Tehran, Iran.
- ²³ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁴ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ²⁵ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- ²⁶ Also at Università della Basilicata, Potenza, Italy.
- ²⁷ Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- ²⁸ Also at Università degli Studi di Siena, Siena, Italy.
- ²⁹ Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.
- ³⁰ Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
- ³¹ Also at University of California, Los Angeles, Los Angeles, USA.
- ³² Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ³³ Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
- ³⁴ Also at University of Athens, Athens, Greece.
- ³⁵ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ³⁶ Also at Paul Scherrer Institut, Villigen, Switzerland.
- ³⁷ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ³⁸ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ³⁹ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁴⁰ Also at Adiyaman University, Adiyaman, Turkey.
- ⁴¹ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁴² Also at The University of Iowa, Iowa City, USA.
- ⁴³ Also at Mersin University, Mersin, Turkey.
- ⁴⁴ Also at Ozyegin University, Istanbul, Turkey.
- ⁴⁵ Also at Kafkas University, Kars, Turkey.
- ⁴⁶ Also at Suleyman Demirel University, Isparta, Turkey.
- ⁴⁷ Also at Ege University, Izmir, Turkey.
- ⁴⁸ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁴⁹ Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
- ⁵⁰ Also at University of Sydney, Sydney, Australia.
- ⁵¹ Also at Utah Valley University, Orem, USA.
- ⁵² Also at Institute for Nuclear Research, Moscow, Russia.
- ⁵³ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁵⁴ Also at Argonne National Laboratory, Argonne, USA.
- ⁵⁵ Also at Erzincan University, Erzincan, Turkey.
- ⁵⁶ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁵⁷ Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
- ⁵⁸ Also at Kyungpook National University, Daegu, Korea.